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13. ABSTRACT (Maximum 200 words)

The main goals of this project ("Internal consistency of meteorological data obtained with a volume-imaging, multi-receiver radar wind profiler") were (1) to identify as clearly as possible the mathematical relationships between radar wind profiler (RWP) signals and the turbulent atmospheric field in the radar resolution volume; and (2) to develop dynamical and other conservation equations for those properties of the turbulence field that we identify in Part (1).

The mathematical relationships between the radar observables and the atmospheric fields have now been formulated in a very general manner. In contrast to all earlier RWP theories, the new theory allows not only the zeroth moment (backscattered power) but also all higher moments (Doppler shift, spectral width, etc.) of the Doppler spectrum to be rigorously expressed in terms of statistics of the velocity and refractive-index fields in the RWP's resolution volume.

The theoretical results have been illustrated and enhanced by the analysis of RWP measurements and fine-wire, in-situ turbulence measurements.

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Internal Consistency of Meteorological Data Obtained with a Volume-Imaging, Multi-Receiver Radar Wind Profiler

(DAAD 19-00-1-0527)

Final Progress Report

Submitted to the Army Research Office
on 26 May 2004

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List of Appendixes, Illustrations and Tables

None.

Statement of the problem studied

Radar wind profilers (RWPs) are the most widely used ground-based remote sensors in operational meteorology and they are among the most versatile instruments in the atmospheric sciences (e.g., Doviak and Zrnic 1993). State-of-the-art RWPs are so reliable and accurate that inconsistencies in the measurements are no longer necessarily the result of instrumental insufficiencies but often the result of insufficiencies in the theory that is used to retrieve meteorological information from the radar raw data. In other words, further progress in RWP technology is no longer limited by insufficiencies in hardware and software technology but by our inability to fully understand the data. The advent of multi-receiver RWPs like the University of Massachusetts' Turbulent Eddy Profiler (TEP) has added a new dimension to this problem.

The main goal of this project was to enhance existing RWP theory such that the RWP observables (e.g., the zeroth, first, and second moment of the Doppler spectra) can be rigorously expressed in terms of (i) radar characteristics and (ii) deterministic and statistical characteristics of structure and evolution of the clear-air refractive-index field in the RWP's resolution volume. A second objective was to discuss the theoretical results in the context of measured data.

Summary of the most important results

Theoretical development:

For more than a decade, it has been known that vertically pointing RWPs often measure time-averaged Doppler velocities with magnitudes considerably larger than the magnitude of time-averaged vertical wind velocities. This has led to the consensus in the community that there are systematic differences between the radial (vertical in the case of a vertically pointing RWP) wind velocity and the Doppler velocity (the velocity obtained from the first normalized moment of the Doppler spectrum). Empirical results and simple models for mechanisms that may cause such systematic differences, or biases, were documented, e.g., by Muschinski (1996) and Worthington et al. (2001). Muschinski et al. (1999) were the first to use large-eddy simulation (LES) data to synthesize realistic RWP raw data. They processed these synthetic RWP signals but they found no biases, suggesting that the biases commonly found in measurements are caused by phenomena that are not captured by LES.

Along the lines of an earlier theoretical development by Muschinski (1998), Tatarskii and Muschinski (2001) theoretically investigated the bias caused by a finite Bragg wave vector component of the spatial quadrature spectrum of the refractive-index and radial-wind velocity fluctuations.

Recently, Muschinski (2004) has developed a theory that allows, in principle, all higher moments of a RWP Doppler spectrum to be expressed in terms of the antenna pattern, the pulse and receiver characteristics, and the deterministic and statistical characteristics of the velocity field and the refractive-index field in the RWP's resolution volume. This new theory, which is the main accomplishment of this project, relaxes a number of (unnecessary and often unrealistic) a-priori assumptions that were used in earlier theories. These assumptions include

- homogeneity of the velocity and refractive-index characteristics across the RWP's resolution volume
- homogeneity of the velocity and refractive-index characteristics during the RWP's dwell time
- Gaussian turbulence spectra
- the validity of the Fraunhofer approximation (which implies that the refractive-index correlation lengths are small compared to the RWP's resolution volume)
- the traditional (global) version of Taylor's frozen-turbulence hypothesis.

The most important achievement of the new theory (Muschinski 2004) is that it provides a rigorous first-principle approach to the higher moments (Doppler shift, spectral width, etc.) of the RWP Doppler spectra. In the equations for the Doppler shift and for the spectral width, there now appear a number of new terms that allow observed biases to be interpreted in terms of meteorological quantities. That is, the new theory provides guidance through what has been unexplored territory until recently.

Combining the new theory with a number of recent achievements in the mathematical community, Muschinski et al. (2004c) outline directions of further advancements in RWP theory and RWP applications in the near future.

Technique development and turbulence studies:

The increased theoretical understanding of the RWP measurement process has led to an increased awareness of possibilities to enhance RWP capabilities into new directions, particularly multi-receiver RWP and multi-frequency RWP. During the project duration, the Principle Investigator was the leader of the CIRES/NOAA-ETL Profiler Development Group (PDG). One of the main achievements of that group has been the first implementation of Range Imaging (RIM) at a UHF RWP (Chilson et al. 2003). Independently of that work, the P.I. contributed to the interpretation of data observed with a new S-band FMCW radar developed by the University of Massachusetts (Ince et al. 2003).

The understanding of atmospheric turbulence is key to the understanding of RWP signals. One important aspect of atmospheric turbulence is intermittency. The P.I. took advantage of high-resolution turbulence measurements obtained during the field experiment CASES-99 and investigated characteristics of small-scale and large-scale intermittency in the nocturnal boundary layer and the residual layer (Muschinski et al. 2004b). Dr. Wyngaard, supported through a subaward of this ARO grant, provided a theoretical analysis of the energy transfer in fully developed turbulence (Wyngaard 2002). His analysis could be useful in modeling energy transfer in nonstationary, inhomogeneous flows.

The statistics of radar reflectivities observed simultaneously with the collocated TEP and UMass S-band FMCW radar in the convective boundary layer have been analyzed (Muschinski et al. 2004a). Both the TEP and S-band reflectivities exhibit lognormal probability densities, as expected (e.g., Muschinski et al. 2004b). A more systematic study based on a longer, cleaner dataset, however, is needed to explore this issue in more depth. A follow-up proposal aiming in that direction was submitted by the P.I. to ARO in October 2003 and is currently under review.

Listing of all publications and technical reports supported under this grant or contract

The six (6) journal papers authored or co-authored by the P.I. (Muschinski) and listed under (a) and (d) can be downloaded from http://www.etl.noaa.gov/~amuschinski/publications/.

(a) Papers published in peer-reviewed journals:

Chilson, P. B., T.-Y. Yu, R. G. Strauch, A. Muschinski, and R. D. Palmer, 2003: Implementation and validation of range imaging on a UHF radar wind profiler. *J. Atmos. Oceanic Technol.*, **20**, 987-996.

Ince, T., S. J. Frasier, A. Muschinski, and A. L. Pazmany, 2003: An S-band frequency-modulated continous-wave boundary layer profiler: Description and initial results. *Radio Sci.*, **38**, 1075, doi: 10.1029/2001RS002586*.*

Muschinski, A., 2004: Local and global statistics of clear-air Doppler radar signals. *Radio Sci.,* **39**, RS1008, doi: 10.1029/2003RS002908.

Tatarskii, V. I., and A. Muschinski, 2001: The difference between Doppler velocity and real wind velocity in single scattering from refractive-index fluctuations. *Radio Sci.,* **36**, 1405-1424.

Wyngaard, J. C., 2002: On the mean rate of energy transfer in turbulence. *Phys. Fluids*, **14**, 2426-2431.

(b) Papers published in non-peer-reviewed journals or in conference proceedings:

None.

(c) Papers presented at meetings, but not published in conference proceedings:

Muschinski, A., P. Lopez-Dekker, S. J. Frasier, and P. B. Chilson, 2004a: Small-scale intermittency in the mixed layer observed with a volume-imaging UHF radar wind profiler. Oral presentation at the National Radio Science Meeting (5-8 January 2004, Boulder, Colorado).

(d) Manuscripts submitted, but not published:

Muschinski, A., R. G. Frehlich, and B. B. Balsley, 2004b: Small-scale and large-scale intermittency in the nocturnal boundary layer and residual layer. *J. Fluid Mech.*, in press.

Muschinski, A., V. Lehmann, L. Justen, and G. Teschke, 2004c: Advanced Radar Wind Profiling. Accepted by internal review (NOAA-ETL). To be submitted to *Meteorol. Z.*

(e) Technical reports submitted to ARO:

Interim Progress Report 2001 (29 March 2002)

Interim Progress Report 2002 (31 March 2003)

List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project:

None.

Report of Inventions (by title only):

None.

Bibliography

Chilson, P. B., T.-Y. Yu, R. G. Strauch, A. Muschinski, and R. D. Palmer, 2003: Implementation and validation of range imaging on a UHF radar wind profiler. *J. Atmos. Oceanic Technol.*, **20**, 987-996.

Doviak, R. J., and D. S. Zrnic, 1993: *Doppler radar and weather observations*. 2nd edition, Academic Press, San Diego, Calif., 562 pp.

Ince, T., S. J. Frasier, A. Muschinski, and A. L. Pazmany, 2003: An S-band frequency-modulated continous-wave boundary layer profiler: Description and initial results. *Radio Sci.*, **38**, 1075, doi: 10.1029/2001RS002586.

Muschinski, A., 1996: Possible effect of Kelvin-Helmholtz instability on VHF-radar observations of the mean vertical wind. *J. Appl. Meteor*., **35**, 2210-2217.

Muschinski, A., P. P. Sullivan, D. B. Wuertz, R. J. Hill, S. A. Cohn, D. H. Lenschow, and R. J. Doviak, 1999: First synthesis of wind-profiler signals on the basis of large-eddy simulation data. *Radio Sci.,* **34**, 1437-1453.

Muschinski, A., 2004: Local and global statistics of clear-air Doppler radar signals. *Radio Sci.,* **39**, RS1008, doi: 10.1029/2003RS002908.

Muschinski, A., P. Lopez-Dekker, S. J. Frasier, and P. B. Chilson, 2004a: Small-scale intermittency in the mixed layer observed with a volume-imaging UHF radar wind profiler. Oral presentation at the National Radio Science Meeting (5-8 January 2004, Boulder, Colorado).

Muschinski, A., R. G. Frehlich, and B. B. Balsley, 2004b: Small-scale and large-scale intermittency in the nocturnal boundary layer and residual layer. *J. Fluid Mech.*, in press.

Muschinski, A., V. Lehmann, L. Justen, and G. Teschke, 2004c: Advanced Radar Wind Profiling. Accepted by internal review (NOAA-ETL). To be submitted to *Meteorol. Z.*

Worthington, R. M., A. Muschinski, and B. B. Balsley, 2001: Bias in mean vertical wind measured by VHF radars: significance of radar location relative to mountains. *J. Atmos. Sci.*, **58**, 707-723.

Wyngaard, J. C., 2002: On the mean rate of energy transfer in turbulence. *Phys. Fluids*, **14**, 2426-2431.

Appendixes

None.